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Comparisons of time series from two global models with tide-gauge data

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Abstract. To understand climate change and to predict changes in climate, both atmospheric and ocean models need to be able to reproduce the responses of the system they are estimating. An evaluation of two related global ocean models, using a nine year time series of model sea surface heights and measurements of sea level from a global tide gauge set, shows that the ocean models satisfactorily reproduce the instantaneous local change in sea level. Sea level can be used as a tool to understand a model's ability to simulate sea surface temperature and thus influence atmospheric flows. The implication for climate modeling is that these ocean models can be used to simulate seasonal to decadal variations in global ocean circulation when coupled to high quality atmospheric models.

Introduction

Modeling of the global ocean circulation has advanced quickly in the last five years producing four dimensional simulations over longer time periods with smaller space resolution [*Semtner,* 1995]. Ocean models need to reproduce sea level (SL) fluctuations on interannual and decadal time scales if the cause and effect of changes in our oceans, including climate change and prediction (in conjunction with atmospheric models), are to be investigated. Such SL changes are indicative of changes in currents and often in heat transport as well. This paper shows such a comparison covering up to pentad variations. There have been previous studies comparing models and tide gauge data sets to determine how well they simulate the ocean's variability. These studies have been, for the most part, in the tropical regions of the Pacific [e.g. *Enfield and Harris,* 1995] using coarser resolution models, with lower frequency wind forcing. It is not intended to compare the results presented here with these others because of the multitude of differences between specific models and how they are forced. This paper will show that two global models, which are being used to help understand ocean dynamics by a large number of investigators, adequately represent the local instantaneous SL. These two models are: 1) the average 1/4° resolution Semtner-Chervin or Parallel Ocean Climate Model (POCM) [*Stammer et al.,* 1996], and 2) a related average 1/6° resolution model, the Los Alamos National Laboratory (LANL) model [*Fu and Smith,* 1996].

To evaluate the accuracy of the Topex/Poseidon satellite, a tide gauge data set was created and made available to researchers: the WOCE "Fast Delivery" Sea Level set [*Mitchum,* 1994; *Kilonsky and Caldwell,* 1996]. This data set can be used to evaluate simulations of ocean circulation from the two related global ocean models. Both models were spun up from observed temperature and salinity fields for about 40 years. The POCM used 3-day 10 m wind stress fields from the European Centre for Medium Weather Forecast (ECMWF) for 1987 through 1995. The second model, LANL, was run for the period of 1990 through 1994 with the same forcing; and its 1993-94 output is included in some of the comparisons. Both models have a time step of a half an hour. The models use the *Barnier et al.* [1995] monthly climatological surface heat fluxes. Time series of the model sea surface height (SSH), averaged over 60 km and sampled every three days, were created at the locations of the tide gauges. The approximate locations of these tide gauge stations are shown in Figure 1. Similarly, the SL data were subsampled from daily values (and using a seven day low pass filter) to a 3-day time series to correspond to the same sampling of the model with an inverse barometer effect removed from the observational data.

The mean of all the station correlations, computed between the POCM model and tide gauge data (with a long term mean removed), for the period of 1988 through 1995, is .45 +/-.29 (median is 0.50). This explains 20% of the observed variance and includes using maximum correlations offset by up to 6 days to allow for numerical dispersion effects. At many stations, the correlation between observations and the model output is high, but at others there is no correlation. The next sections seek to explain the discontinuity between the observations and model estimates of SL by looking at the annual harmonic and the anomalies (SL minus the annual signal), followed by examining the problems due to the wind field, and finally, looking at the models' resolution to determine if higher resolution allows the model to reproduce the observations more accurately. The results presented below include the removal of a long term mean from each of the time series.

Annual and anomalous SSH time series

The model and observational signals can be separated into annual and anomalous parts by harmonic analysis.

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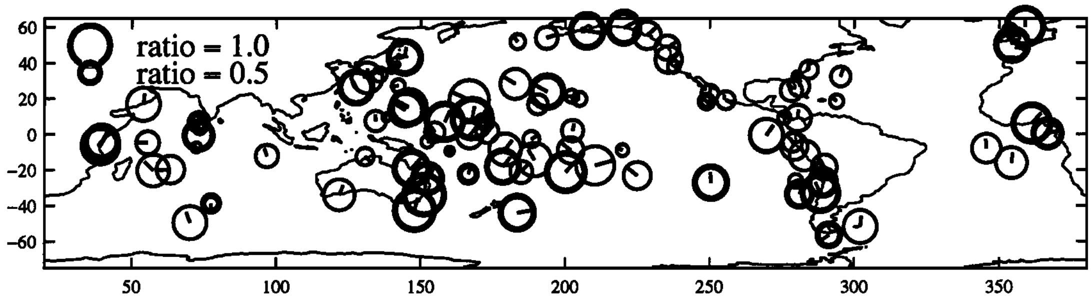

Figure 1. Comparison of annual signal from POCM model and tide gauge data. Circle size equals the amplitude ratio of the model/data (bold) or data/model (thin). The radial line is the phase difference; in phase at 12:00.

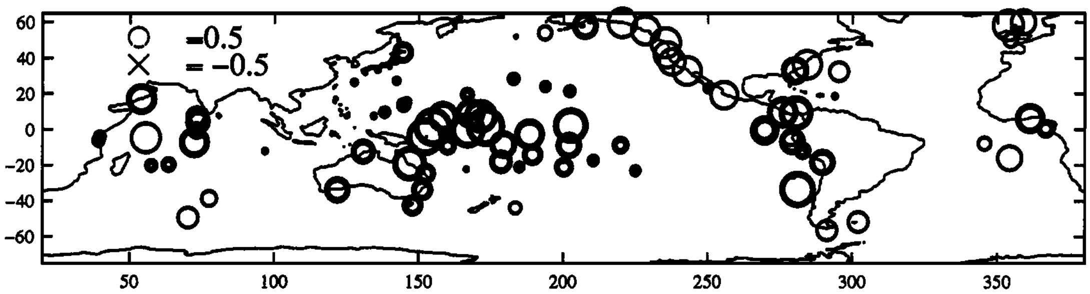

Figure 2. Correlations between anomalous SL from POCM and tide gauges; circles: positive correlations; Xs: negative. Circle diameter is the correlation value. Bold circles: data available before 1991.

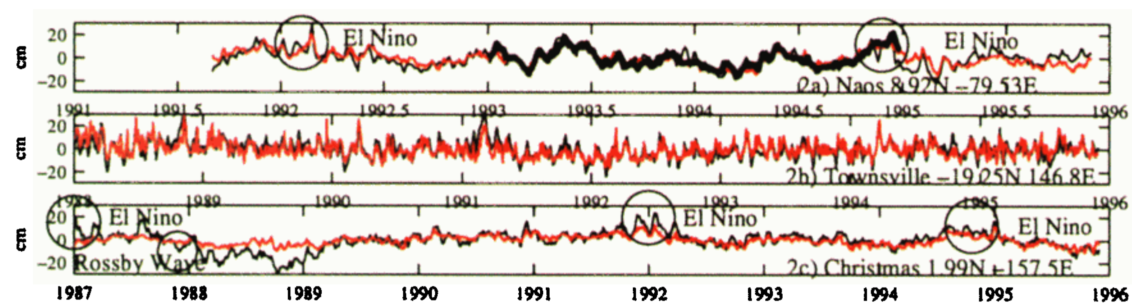

Figure 3. a) Time series of the SL as measured by the tide gauge (thin line), the 1/4° POCM model (red line) and the 1/6° LANL model (bold line) at Naos Island, south of Panama b) For Townsville c) For Christmas Island. The horizontal scales are different for each plot.

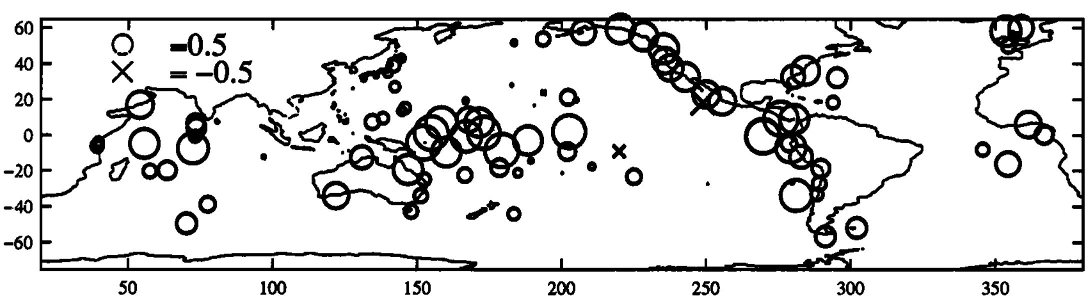

Figure 4. same as 1b (the annual harmonic has been removed), except for the period Sept. 1991-1995.

Figure 1 shows the ratio of the amplitudes of the annual harmonic (circle size) and the difference in phase (radial line) between the two time series at each station. Most of the amplitude ratios are between 0.5 and 1. When the ratio is low, it is usually the model that has underestimated the ocean's variability. The two signals are in phase when the radial line is at 12 o'clock. If the line lies between 6 and 12 o'clock, the model leads the in situ data, for example in the mid-latitudes of the North Pacific. *Stammer et al.* [1996] suggest that both the model's low amplitude and the mismatch in phase may be due to inaccuracies in the ECMWF sea surface heat fluxes. The annual cycle is on the order of 20% of the total signal (19% for the in situ and 26% for the model), with the anomalous portion (total - annual harmonic) much more important in the tropics and at high latitudes (>50°). Two locations, Darwin (12.47°S 130.85°E) and Honiara (9.43°S 159.96°E), having particularly bad annual comparisons, are in areas where the flow is complicated by semi-annual signals or intricate topography. Although topography can be specified at the grid size without appreciable smoothing in a free-surface model, many details of the bathymetry are erroneous in existing datasets.

With the annual harmonic removed (Figure 2), the mean correlation is 0.37 +/- 0.30 (median 0.40) for the period 1988 through 1995. Anything above 0.07 is a significant correlation for most of the stations. The significance test determines whether the correlation is different from zero, not if the two series are the same. Although the mean over all stations is low, there are regions, along the coastlines and in the tropics, where the correlations are much larger than the mean. As examples of coastal comparisons, Figure 3a shows three coincident time series, POCM, LANL, and tide gauge data, at Naos Island south of Panama in the Pacific (correlation about 0.8) and a longer series (Figure 3b) at Townsville on the northeast coast of Australia (correlation about 0.7). The anomalous signal at Naos for which POCM and the tide gauge records show the winter of 1991/1992 and 1994/1995 El Niño peak responses in the local SL, are well correlated between all three time series. These remotely forced changes in the SL are seen both north and south of the equator along the eastern edge of the Pacific in the model output and the tide gauge data. The model simulates the northward traveling coastal Kelvin waves forced by the equatorial trapped waves traveling across the whole of the tropical Pacific. Figure 3c shows the El Niño events in November of 1991 and 1994 at Christmas Island (2°N 157.5°W), which are seen at Naos Island about a month later. This fits the estimated wave speed (2.8 m/s) as given by *Delcroix et al.* [1994]. The reason that the correlations along the western coast of North America are higher than those along South America is because of the difference in the time span of the data record. This is discussed in the next section.

Overall, spectral analysis of each station show no trends other than too low signal amplitude in the model data compared to the in situ data when the correlations are low. Sometimes, higher frequency events are not as energetic in the model as in the tide gauge measurements.

Importance of forcing field

To help explain the low mean correlations, the effect of the model's forcing field (wind stress) is examined. It is important to have accurate and timely wind forcing to estimate the fluctuations in SL using an ocean circulation model for two reasons; both should be obvious. First, local SL can not be accurately simulated if it includes effects forced at a remote location but not simulated in the model (either because a model is regional or because the simulation does not include the time period which would have forced the remote event). And second, without accurate local forcing, the model will not to be able to simulate the circulation of the ocean at a given location.

Christmas Island (Figure 3c), at 2°N, 157.5°W, can be used to demostrate the first problem. The POCM model, forced with wind stress data beginning in 1987, does not include the December 1986 El Niño; and any delayed oceanic response driven by the 1986 wind stresses will not be found in the model estimation of SL. *Delcroix et al.* [1994] have shown that equatorially trapped Kelvin waves are reflected from the west coast and return as first baroclinic Rossby waves. The representative increase in SL by the appearance of downwelling Kelvin waves is observed in the SL as measured from the tide gauge (black line in Figure 3c) in 1987. This is at the early part of the model run, while the model is adjusting to the new forcing function. A Rossby wave generated at the eastern edge as a reflection of the Kelvin wave reaching the eastern boundary can also be seen near the end of 1987 with a decrease in the SL measured by the tide gauge. Other tropical stations show similar mismatches between the observations and the model estimates near the equator in 1987/1988. As can be seen in Figure 2c, the model has failed to simulate both these features (red line).

For the second problem, a comparison of correlations between two separate periods of the time series gives a clear example of the improvements made to the wind field in September of 1991 by ECMWF [*Simmons*, 1994]. Figure 4 shows correlations for the whole globe calculated only for the period September of 1991 through 1995. This figure can be compared directly to the Figure 2 by looking at the change in the correlations for the stations which have bold lines in Figure 2. The mean of the correlations for Figure 3 is 0.42 +/- 0.28, which is slightly better than 0.34 +/- 0.29, the mean of the correlations for the period of 1988 through 1991 (no figure given). There is significant improvement at some of the stations along the western South American coast, for example at Baltra (0.4°S, 90.3°W , 0.5 to 0.9) and at some stations in the South Pacific, for example, Pago Pago (14.3°S, 170.7°W, 0.1 to 0.8). Figure 4 and the increase in some of the correlations suggest that the wind field has improved rather than the model physics failing to ininclude some low frequency variability of SL.

Still the correlations remain uncomfortably low in the mid-latitudes. Part of the reason is because the wind stress fields are not as well known in the subtropics of the Pacific, and thus, the model does not estimate the variation in SSH well. Several studies [e.g. *Rienecker et al.*, 1996] which compare different wind forcing fields in the North Pacific for a given model, show plots with varying differences in the wind fields, especially at mid-latitudes. With few observed data values contributing to the wind estimate in the the North Pacific between 10°N and 30°N, the models should not be expected to reproduce higher frequency events accurately. Also, instabilities in these eddy-rich areas, whose variations can not be predicted, will always, to some degree, lead to lower correlations. Contrary to the northern hemisphere, between 10°S and 30°S and especially in the western half of the Pacific, the correlations are somewhat higher because, with more islands, more observations are incorporated into the estimates of the wind field. It will be interesting to find out how scatterometer winds (expected to be a more accurate measure of the wind field in the open ocean) modify the model's SL.

Model Resolution

For the most part, the comparisons shown above have been for a model with a nominal resolution of 1/4°. Is part of the mismatch between tide gauge measurements and model estimates, due to a lack of resolution? The LANL global model with somewhat higher resolution can be used to help find the answer. SSH values from the LANL model, with only a mean removed for the period 1993 through 1994, were correlated with the SL data from the tide gauges. (The two years of data from the 1/6° model are just barely enough data to compute an annual signal and so the annual signal is not removed from any of the data sets for this comparison.) These data, plotted against the correlations from the same time period for the POCM model (Figure 5), have a mean correlation, for the 1/6° model, of 0.47, while the 1/4° resolution model has a mean correlation of 0.49. In view of the turbulent and unpredictable aspects of ocean circulation in many parts of the world ocean, these values seem remarkably high. The RMS difference between these two sets of correlations is relatively small, 0.16. Thus, from these numbers, the two models closely resemble each other. Some of the stations do not have significant correlation values for either model. The models do differ significantly at several tide gauge locations. The LANL model better represents the Kuroshio and the surrounding area. From these comparisons, the lower resolution model is, in fact, doing a decent job in its representation of the variations in SL, almost as well as the higher resolution model. Thus, it can be used for long term (decades) runs relating to climate with confidence and lower computation costs.

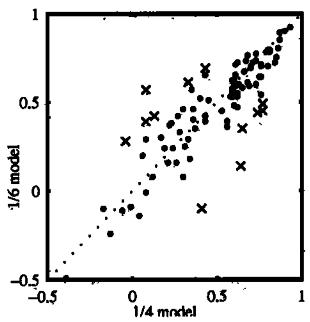

Figure 5. 1/4° model and tide gauge correlations verse 1/6° model and tide gauge correlations, 1993-1994.

Conclusions

This comparison of tide gauge measurements of SL with the Semtner-Chervin POCM and LANL global ocean models' SL shows the two models do an adequate job in estimating the variations in the local SL of the real ocean. Specifically, realistic and accurate wind forcing, both local and remote, is necessary in the accurate estimation of SL; and model resolution improves SL estimation only at latitudes greater than about 35°N. The implication for climate modeling is that ocean models can track seasonal to interannual variations in global ocean circulation when coupled to high quality atmospheric models. Future runs of the models will include using the consistent reanalyzed ECMWF winds from 1979 through 1995 along with scatterometer winds to produce a more accurate wind field over sparsely sampled mid-ocean regions.

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